Characteristic temperatures of exchange biased systems

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Characteristic temperatures in ferromagnetic-antiferromagnetic exchange biased systems are analyzed. In addition to usual blocking temperature of exchange bias, T_B, and the Néel temperature of an antiferromagnet, T_N, the inducing temperature of exchange bias, T_{ind}, has been recently proposed. T_{ind} is the temperature at which the direction of exchange anisotropy is established. We demonstrate that this temperature is, in general, different from T_B and T_N. Measurements of T_{ind}, in addition to T_B and T_N, provide important information about exchange interactions in ferromagnetic-antiferromagnetic heterostructures. © *2007 American Institute of Physics.*
[DOI: 10.1063/1.2769807]

I. INTRODUCTION

Exchange anisotropy appears in hybrid ferromagnetic (F)-antiferromagnetic (AF) systems due to exchange interactions at the F-AF interface.[1] The interfacial exchange creates an additional energy barrier which F magnetic moments have to overcome during the magnetization reversal. The exchange anisotropy is unidirectional and manifests as a horizontal shift of the magnetic hysteresis loop after field cooling. The exchange bias field is determined as the value to which the center of the hysteresis loop is shifted with respect to zero field.[2] This assumes that the AF structure stays stable; a valid assumption unless the total AF magnetocrystalline anisotropy is too low. The latter case leads to AF spins rotating coherently with F spins, and the exchange bias vanishes.[3,4,6] The hysteresis loop is normally shifted in the direction opposite to the cooling field, indicating that the interfacial exchange coupling is ferromagnetic (i.e., it favors parallel orientation of the interfacial F and AF spins). The case of "positive" loop shifts, which may assume antiferromagnetic coupling at the F-AF interface (favoring antiparallel alignment of the interfacial F and AF spins), was described by Nogués *et al.*[7,8]

It is "common knowledge" that exchange anisotropy is established when field cooling a F-AF system through the Néel temperature T_N of the antiferromagnet.[9,10] The exchange bias blocking temperature T_B is the temperature at which the exchange bias disappears. Recently, it has been demonstrated that the direction of exchange anisotropy can be established at a temperature larger than T_B. This temperature is denoted as the exchange bias inducing temperature, T_{ind}.[11]

II. THE PROCEDURE FOR MEASURING THE EXCHANGE BIAS INDUCING TEMPERATURE

The procedure for measuring T_{ind} is as follows. First, the sample is field cooled in a "negative" field ($-H_{FC}$) from temperature T_M ($T_M > T_N$) to a certain temperature T_{switch}. At T_{switch} the sign of the cooling field is changed. Further cooling to the temperature T_m is performed in field $+H_{FC}$. T_m is the temperature at which the hysteresis loop is measured ($T_m < T_B$ must be satisfied). The absolute value of the exchange bias field at T_m is H_m. If the direction of the exchange anisotropy is not established at T_{switch}, then the exchange bias field measured at T_m will be $-H_m$, since it will be induced in a positive cooling field $+H_{FC}$. On the other hand, if the direction of the exchange anisotropy is established at a temperature higher than T_{switch}, changing the sign of the cooling field does not influence the sign of the exchange bias field $+H_m$ measured at T_m. By scanning T_{switch} from T_M down to T_m, the transition temperature T_{ind} will be found at which the direction of exchange anisotropy is established.[12] The dependence of the exchange bias field H_{eb} (measured at fixed T_m) versus T_{switch}, is schematically illustrated in Fig. 1. In the above description we assume that there is no training effect in the system.[13] Otherwise, the transition at T_{ind} would be not from $-H_m$ to $+H_m$, but from $-H_m$ to H_{mTL}, where the last value is the exchange bias field of the first training loop at T_m.
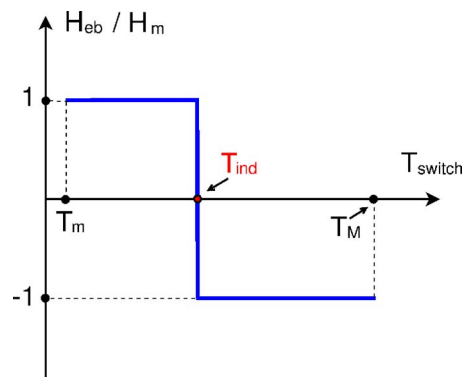

FIG. 1. (Color online) Exchange bias field H_{eb}, measured at temperature T_m as a function of temperature T_{switch}, at which the sign of the cooling field is changed from $-H_{FC}$ to $+H_{FC}$. The temperature is scanning from T_M down to T_m. In case of $T_{ind} < T_{switch} < T_M$, the exchange bias is negative ($-H_m$), since it is induced by a positive cooling field $+H_{FC}$. For $T_m < T_{switch} < T_{ind}$ the exchange bias is positive ($+H_m$), because it is induced by a negative cooling field $-H_{FC}$. T_{ind} is the temperature at which the direction of the exchange anisotropy is established.

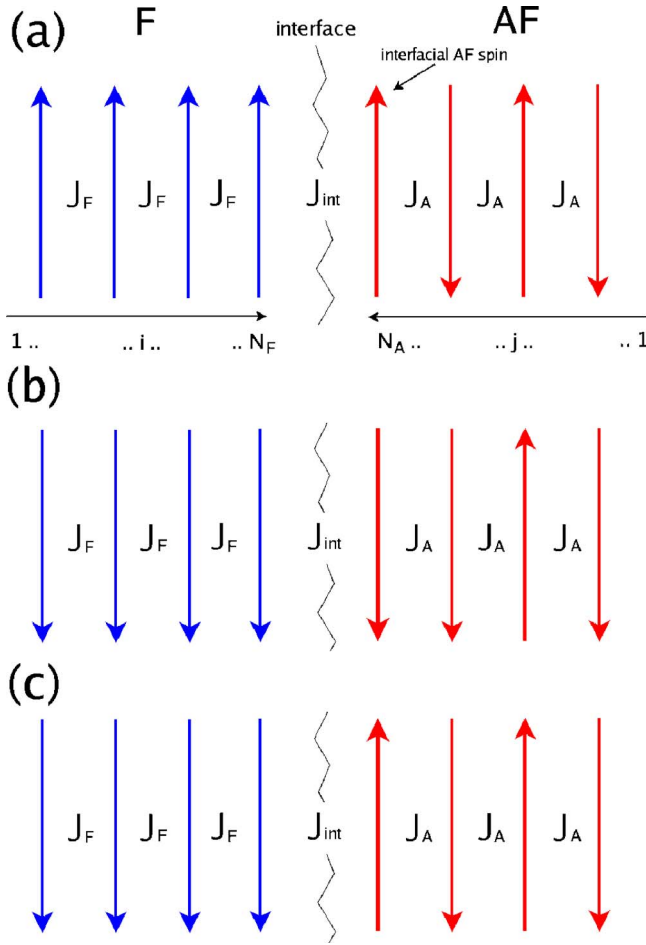a)Electronic mail: alexey@dobrynin.org

FIG. 2. (Color online) Schematic view of the one-dimensional F-AF system. (a) The system is cooled in a "positive" field, and the ground state is formed. (b) $J_{int} > J_A$: the interfacial AF spin rotates coherently with the F part, and the exchange bias field is determined by J_A. (c) $J_{int} < J_A$: the interfacial AF spin stays stable during the magnetization reversal, and the exchange bias field is determined by J_{int}.

III. MODEL OF INTERACTIONS IN A FERROMAGNETIC-ANTIFERROMAGNETIC SYSTEM

In order to understand the origin of the inducing temperature and its difference from the blocking temperature we consider a one-dimensional F-AF model system, which is schematically shown in Fig. 2. In the assumption that the exchange interactions exist only between localized nearest-neighbor spin magnetic moments, the exchange Hamiltonian of the system may be written as

$$H_{ex} = -J_F \sum_{i=1}^{N_F-1} \mathbf{S}_{\mathbf{F}_i} \mathbf{S}_{\mathbf{F}_{i+1}} - J_A \sum_{j=1}^{N_A-1} \mathbf{S}_{\mathbf{A}_j} \mathbf{S}_{\mathbf{A}_{j+1}} - J_{int} \mathbf{S}_{\mathbf{F}N_F} \mathbf{S}_{\mathbf{A}N_A}.$$

(1)

Here, $\mathbf{S_F}$ and $\mathbf{S_A}$ are F and AF spin magnetic moments respectively, $J_F > 0$ is the exchange coupling constant between F spins, $J_A < 0$ is the exchange coupling constant between AF spins, and $J_{int} > 0$ is the exchange coupling constant between interfacial F and AF spins $\mathbf{S}_{\mathbf{F}N_F}$ and $\mathbf{S}_{\mathbf{A}N_A}$.

The stabilities of the F, AF, and interfacial F-AF coupling are modeled by the first, second, and third terms of Eq. (1), respectively. The third term gives rise to the exchange

anisotropy. The direction of the exchange anisotropy is determined by the orientation of $\mathbf{S}_{\mathbf{A}N_A}$, since in the ground state F spins are parallel to the interfacial AF spin, as imaged in Fig. 2(a). We define $T_{N_{int}}$ as the temperature at which the AF exchange interaction between $\mathbf{S}_{\mathbf{A}N_A}$ and $\mathbf{S}_{\mathbf{A}N_A-1}$ is established. The temperature at which the interfacial F-AF interaction (i.e., the interaction between $\mathbf{S}_{\mathbf{F}N_F}$ and $\mathbf{S}_{\mathbf{A}N_A}$) is established is designated as T_{FAF}. $T_{N_{int}}$ is proportional to J_A, while T_{FAF} is proportional to J_{int}. In the many dimensional case these freezing temperatures are proportional to the product of the corresponding exchange coupling constant and the corresponding coordination number. It is necessary to stress that in real situations other parameters not considered in our model may influence the values of the freezing temperatures (in particular, magnetocrystalline anisotropy). Such interactions are generally much weaker than the exchange interactions, and the corresponding energy contributions could be introduced as perturbations of the exchange coupling constants.

Assume that the system is cooled in a positive field through T_N, and the direction of the field is changed just after passing T_N. $T_{N_{int}}$ is less than T_N due to the reduced AF coordination number at the interface. Therefore, the interfacial spin can still be aligned by the external negative field yielding the configuration shown in Fig. 2(b). However, this is not the ground state of the system, since $\mathbf{S}_{\mathbf{A}N_A}$ favors antiparallel alignment with $\mathbf{S}_{\mathbf{A}N_A-1}$. The ground state corresponds to that shown in Fig. 2(a), and, therefore, the direction of exchange anisotropy is established when passing T_N, i.e., $T_{ind} = T_N$ for the one-dimensional case.

In the three-dimensional system, the situation described above is not the only possibility. Most of the models of exchange bias assume a type of frustrated interfacial AF spin configuration.[14] In particular, uncompensated interfacial AF spins were found to be the reason of exchange bias in many systems.[15–18] Such an uncompensated AF spin has both parallel and antiparallel AF neighbors, and, therefore, it is in a frustrated state. Similar configurations may exist if other mechanisms are involved in the exchange anisotropy, such as spin-flop coupling,[5,19,20] hybrid F-AF domain walls[21] or partial AF domains.[22] The frustrated state of the interfacial AF spins in combination with the reduced AF coordination number at the interface leads to a situation wherein $T_{N_{int}}$ is less than T_N. In this case, the interfacial AF spins can be reoriented by an external field at a temperature intermediate to $T_{N_{int}}$ and T_N.[23] Upon further field cooling, the frustrated interfacial AF spin will couple to the neighboring AF spin with antiparallel orientation, forming the ground state. This direction will be the easy direction of magnetization of the whole system. The temperature at which the most favorable orientation of the interfacial AF spins is established is the exchange bias inducing temperature.

IV. THE DISTINCTION BETWEEN INDUCING, BLOCKING, AND NÉEL TEMPERATURES

While the fact of the difference of T_B and T_N is well established,[24] a strict definition of T_B is missing. One common way is to determine T_B as the maximal temperature at

which exchange bias exists after field cooling a F-AF system through T_N. We find it appropriate to accept this as a definition of T_B. This way, T_B and T_{ind} are easily measurable values, and in different situations correspond to real freezing temperatures T_N (also measurable), T_{FAF}, or $T_{N_{int}}$. Below we discuss these possibilities.

Obviously, exchange bias cannot appear once all interfacial exchange interactions are established. Thus, $T_B = \min(T_{FAF}, T_{N_{int}})$. If the interfacial F-AF exchange coupling is weaker than the exchange coupling between the interfacial AF spins and the rest of the AF part ($J_{int} < J_A$ for the one dimensional case), then the measurements of T_B will yield T_{FAF}, while T_{ind} corresponds to $T_{N_{int}}$ (frustrated case) or T_N (nonfrustrated case), and, therefore, $T_B < T_{ind}$. This also means that the interfacial AF spins stay stable during the magnetization reversal at T_m, and the exchange bias value is determined by J_{int}. This situation is shown in Fig. 2(c).

If $J_{int} > J_A$ then $T_{FAF} > T_{N_{int}}$. The interfacial uncompensated AF spins (i.e., those, responsible for exchange bias) will rotate coherently with the F spins during the magnetization reversal at T_m, and the exchange bias value is determined by J_A. If the interfacial AF structure is frustrated, then the measurements of both T_B and T_{ind} will yield $T_{N_{int}}$. If $J_{int} > J_A$ and the interfacial AF structure is not frustrated, T_B will be less than $T_{ind}(=T_N)$, because T_B still corresponds to $T_{N_{int}}$, while the direction of exchange bias will be set at T_N, as discussed for the one-dimensional case. This situation corresponds to that shown in Fig. 2(b).

A slight difference between T_B and T_{ind} has been recently observed in oxidized Co nanocluster films.[11] This difference is expected to be larger for systems with rough F-AF interface, where J_{int} is significantly reduced as compared to that in natively oxidized or epitaxially grown F-AF systems.[25,26]

Sometimes the technique developed by Soeya et al.[27] is used to determine T_B. With this method a sample is first field cooled to temperature T_m, then warmed up at zero field to a certain temperature, at which the magnetic field of the opposite sign is applied, and the sample is cooled back to T_m at this field. The temperature at which the direction of the exchange bias, measured at T_m, can be changed, is accepted as T_B. Apparently, this technique will yield the same result as the technique for measuring T_{ind} unless there is some thermal hysteresis in the system. Thus, the method of Soeya et al. will not yield the true T_B value in all situations.

V. CONCLUSIONS

In this paper we have demonstrated that it is necessary to distinguish between the temperature at which the direction of exchange anisotropy is established (T_{ind}), the maximal temperature at which exchange bias may exist (T_B), and the Néel temperature of the antiferromagnet (T_N) in F-AF heterostructures. A modified method of measuring T_{ind} was proposed, and the method yielding the true T_B value was highlighted. Moreover, important information about interfacial F-AF structure and exchange interactions may be extracted by comparing these three temperatures. The case of $T_{ind} < T_N$ assumes a frustrated interfacial AF structure in a system, otherwise $T_{ind} = T_N$. If $T_B = T_{ind} < T_N$, the interfacial F-AF in-

teractions are stronger than those between the interfacial AF spins and the rest of the AF part, assuming rotation of the interfacial AF spins during the magnetization reversal. The exchange bias value in this case is determined by the latter AF exchange coupling. In the case of $T_B < T_{ind} < T_N$ the interfacial AF spins stay stable, and the exchange bias field is determined by the interfacial F-AF exchange coupling. Systematic comparisons of T_{ind}, T_B, and T_N in different exchange biased systems will help in revealing the involved exchange mechanisms, and lead to better understanding of the exchange bias phenomenon.

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